CAPI
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A roadmap to support decision making on the implementation of vertical farming in Canada.

A *Research* Report prepared for CAPI by
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Research
Report

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The Canadian Agri-Food Policy Institute's missions is to lead policy development, collaborate with partners and advance policy solutions within agriculture and food.

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Note from CAPI

CAPI recognizes the importance of fostering and mentoring the next generation of thought leaders emerging from Doctoral programs across Canada, who are working in multi-disciplinary fields. Through this program, CAPI offers a small, innovative group of young students the opportunity to apply their new found knowledge and expertise to some of agriculture's most critical policy issues.

The third cohort of CAPI Doctoral Fellows (2022-2024) was tasked with focusing their research on the intersection of agricultural trade, the environment and food security and this paper is the result. In light of recent trade disruptions, food security concerns and climate change commitments, CAPI is interested in how these factors are impacting Canadian agriculture and agri-food and the policy implications. This Group paper is the final deliverable in the second year of the two-year program, showcasing the interdisciplinary nature of the fellows' research as it relates to a roadmap to support decision makers in addressing the challenges and opportunities in implementing vertical farming and sustainable food systems in Canada.

This Fellowship is supported in part by the RBC Foundation through RBC Tech for Nature as part of CAPI's larger environmental initiative, Spearheading Sustainable Solutions.

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Key Takeaways

- Vertical farming, which is more generally defined as "an array of production methods for continuous crop production in artificial environments using technology and configurations to elevate crops in a vertical fashion", has the potential to contribute to a more sustainable food system in Canada.
- This is particularly the case given Canadians' heavy reliance on imported fruit and vegetables as an important source of nutritious food, for both the general population and those living in Northern communities.
- Vertical farming has the potential to supply domestically grown fruits and vegetables more sustainably to address food security while boosting supply chain resilience in the face of shocks and vulnerabilities from climate change impacts in traditional growing regions, and from trade disruptions.
- However, challenges remain for greater expansion of vertical farming in Canada due to its heavy reliance on energy inputs, new technologies, the regulatory and trade policy environment, and consumer and farmer resistance to this high technology form of agricultural production.
- The paper's proposed roadmap to guide government and industry decision-makers around the implementation of vertical farming in Canada can lead to an adaptive, enabling policy and regulatory environment, that ensures there is engagement among stakeholders, greater education and awareness of the opportunities VF can provide the general public and those in Northern communities, and innovative responses from investments in the sector so it can grow and contribute to a more sustainable food system in Canada.
- Potential solutions include increased public and private investments in research, new technologies, infrastructure and workforce skills, as well as incentives that encourage clean energy use and support locally adaptable configurations for urban and northern communities. Promoting education and awareness of the public as well as more conducive trading rules that support sustainable food systems will also be important.

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Abstract

Canada's food system is globally recognized for its safety, quality, and food security per international reports, yet the country's reliance on fruit and vegetable imports poses risks to the accessibility of healthy diets and to the resilience of the supply chain. This report examines the potential of ***vertical farming*** (VF) to manage these challenges and proposes a roadmap to navigate decision-making on expanding this concept of farming to support Canada in transitioning toward a more sustainable food system. It involves a two-fold approach: first, an analysis of current trade-related vulnerabilities facing the supply of fruits and vegetables by province, as well as an analysis of the environmental, socio-economic, and trade policy interventions that must be considered in decision-making processes if VF were to be expanded as potential solutions contributing to the sustainability of food systems in Canada. The second one is a proposed roadmap to support decision making in expanding VF in Canada, designed from the findings of the preceding part, and considering the principles of adaptive governance and management to ensure that their implementation remains viable amidst uncertainty and change.

1. Introduction

Canada's food system is considered top performing in terms of food security. In fact, in 2022 Canada was ranked 1st in terms of food safety and quality, and 7th in terms of food security per the Global Food Security Index published by the Economist (Economist Impact, 2022). However, Canada's relatively high dependence on imports of fruits and vegetables makes it vulnerable to disruptions at different points of the food supply chain (Zerriffi et al., 2022). Any such disruption creates a threat to Canadians in accessing healthy diets and to ensure resilience in Canada's fruits and vegetables supply (Bajaj, 2023). *Controlled Environment Agriculture* (CEA) encompasses a range of farming concepts that may help overcome the climatic barriers for producing crops locally and year-round. Since the term CEA is found in the literature with different connotations, Box 1 summarizes the definitions of VF and CEA and related terms used in this paper. Although vertical farming may take place in semi-controlled environments (such as rooftop greenhouses), *indoor vertical farming* is referred to as VF in this study as farming systems i) in highly controlled environments; ii) using vertical configurations of crops; and iii) based on technologies to produce crops on a continuous basis.

Box 1. Vertical Farming, CEA and related concepts.

Protected agriculture

Protected agriculture encompasses a range of regulation techniques for crop growth at the macro and microenvironment levels to "facilitate optimal plant performance, extension of production duration, induction of earliness, and obtaining higher and better-quality yields" (Gruda et al., 2019 pp 325). Considering the wide range of approaches and techniques for regulating the climatic conditions at the macro and microenvironment levels (e.g., individually protected crops), the concept may be better understood by differentiating it from non-protected cultivation, which refers to crop growth in natural systems (Gruda et al., 2019b).

Controlled environment agriculture

Also referred to as a food frontier (Dsouza et al., 2023; Glaros et al., 2022) CEA may be defined as:

- "an array of production methods and building designs" for crop production in artificial environments (Glaros et al., 2022 pp 557).

- "systems where crops are protected from external weather conditions and that have the ability to control, monitor and regulate the microclimate of the cultivation area in order to produce greater yields that are more stable under year-round productions" (Vatistas et al., 2022 pp. 2).

Some authors suggest to CEA as vertical farms and/or plant factories, while other authors also suggest including greenhouses and high tunnels as types of CEA (Engler et al., 2021; Glaros et al., 2022; Vatistas et al., 2022). Glaros et al. (2022) suggests that 'Traditional' CEA designs include high-tunnels and greenhouses, and 'novel' designs of CEA include rooftop greenhouses, container farms, and plant factories.

Greenhouses – GHs

Semi-controlled environment constructions, ranging from facilities using natural sunlight for lighting and temperature control, up to sophisticated structures based on technologies for climate control, or high-tech GHs (Gruda et al., 2019; Vatistas et al., 2022).

Vertical farms

Farming using configurations to "elevate crops in a vertical fashion" (Engler et al., 2021 pp. 2).

High tunnels

A type of greenhouse, based on the form and structure of their cover (Gruda et al., 2019).

Plant factories / Indoor plant factories

The term 'plant factory' is often used in the literature to refer to a type of CEA where agriculture takes place in enclosed facilities (McCartney & Lefsrud, 2018) and where optimal and consistent environmental conditions for plant growth are achieved through the intensive use of technologies, or high-tech systems (He et al., 2021; Shamshiri et al., 2018). Also referred to as indoor plant factories, these highly controlled environment systems are typically configured in the form of vertical farms and operate as factories since they are planned, designed, and operated to produce preestablished quantities, types and quality of crops, on a continuous and/or consistent basis (He et al., 2021).

While Canada has a tradition implementing greenhouses and high tunnels, their contribution to local and year-round production is limited due to the long and cold winters (McCartney & Lefsrud, 2018). In fact, greenhouse production only represents 4% of Canada's domestic supply of fruits and vegetables (Government of Canada, 2023; Statistics Canada, 2023). VF might allow extending the capacity of CEA to produce crops on a continuous basis to remote locations, extreme climatic zones (Bunge et al., 2022; Didenko et al., 2021; He et al., 2021), and/or to regions with limited availability of land (Musa & Basir, 2021; Saad et al., 2021).

However, there are trade-offs associated with implementing VF due to their demand for inputs and resources such as electricity, seeds, fertilizers, and water, also potentially increasing domestic GHGs (Romero, 2023). This, along with uncertainties and challenges associated with their performance on the social and economic dimensions of sustainability, has raised concerns among stakeholders associated with upscaling VF as part of strategies to enhance a food systems' sustainability. Hence, expanding VF as part of a strategy for transitioning towards more sustainable and resilient food systems must be preceded by decision-making processes to create capacity to induce meaningful changes while maintaining the ability of a food system to deliver its desired outcomes despite uncertainty and disruptions (Prosperi et al., 2016). This involves making choices in terms of the desired outcomes of implementing VF in Canada, potential investments and incentives, policy and regulatory interventions, selection of locations, and further research. A necessary step to provide insights into the direction that further efforts on research, policy making, and investments in VF should take in Canada is to define a roadmap to guide decision-making and ensure their suitability facing sustainability goals in the long term (Romero, 2023).

This paper aims to devise a roadmap to support decision-making for VF expansion to help Canada shift towards more sustainable food systems. This will be addressed based on 1) understanding the need to produce fruits and vegetables locally/domestically; 2) acknowledging the considerations in expanding VF in terms of 2.1) environmental interventions, socio-economic interventions; and trade policy interventions; 3) the principles of adaptive governance and adaptive management (Dietz et al., 2003; Folke, 2006; Walker et al., 2004) to ensure a proper context in spite of changes and uncertainty, for the successful implementation of VF.

1.1. Research outline

1.1.1. Research question

What are the steps needed in decision-making if VF were to be expanded as solutions intended to help make food systems in Canada more sustainable?

1.1.2. Research objectives.

Objective 1. Identify the opportunities/need for producing fruits and vegetables locally/domestically in Canada.

Objective 2. Identify environmental, socio-economic, and trade policy considerations for expanding VF in Canada.

Objective 3. Devise a roadmap to support decision making in expanding VF to support Canada in transitioning towards more sustainable food systems.

1.2. Methodology

Part 1. The first section of this research (**Objective 1)** is based on an analysis of current trade-related vulnerabilities facing the supply of fruits and vegetables in Canada by province (**Activity 1.1.**). This will be addressed by using Canada's fruit and vegetable food flows (Bajaj 2023; Bajaj 2023 *in prep*), which allow identifying a) the extent to which Canadian provinces depend on distant regions for their supply of fresh fruits and vegetables, and ii) estimating specific resilience indicators (**Activity 1.2.**), such as import dependence or self-sufficiency ratios, for Canada's individual fruit and vegetable supply. These indicators will help identify regions that are most vulnerable to trade-related supply disruptions and where VF might be needed to reduce vulnerability.

Part 2. The considerations for a successful expansion of VF to support Canada in transitioning towards more sustainable food systems (**Objective 2**) will be addressed by performing a review of literature on their associated i) environmental interventions; ii) social interventions; and iii) trade policy interventions. ***Activity 2.1 environmental interventions*** is aimed at identifying the environmental aspects of VF, based on the review of recent studies assessing their environmental performance. ***Activity 2.2 socio-economic interventions*** aims to identify current social and economic concerns associated with the implementation of VF and also explores potential solutions to address these challenges with a lens of adaptive management. This will be examined by performing a review of the literature and VF census reports on consumer awareness and perception of VF, and identifying producer challenges and opportunities in expanding VF. ***Activity 2.3 trade policy interventions*** is aimed at identifying the current policy space for agricultural support measures under World Trade Organization (WTO) law that can be leveraged to address challenges associated with VF and facilitate solutions for its effective implementation. This will entail a qualitative analysis of relevant rules, including the [S1] Agreement on Agriculture (AoA), the Agreement on Subsidies and Countervailing Measures (SCM Agreement) adjudicatory decisions, and an overview of Canada's agricultural support programs in light of sustainability objectives.

Part 3. A roadmap to guide decision-making in expanding VF to support Canada in shifting towards more sustainable food systems (**Objective 3**) will be devised based on the results of Parts 1 and 2, and by incorporating principles of adaptive governance and adaptive management (Dietz et al., 2003; Folke, 2006; Walker et al., 2004)**.** This will allow devising a roadmap that involves diverse stakeholders at different scales, reduces uncertainty, and provides flexibility to design appropriate and adaptive solutions for continuously changing contexts.

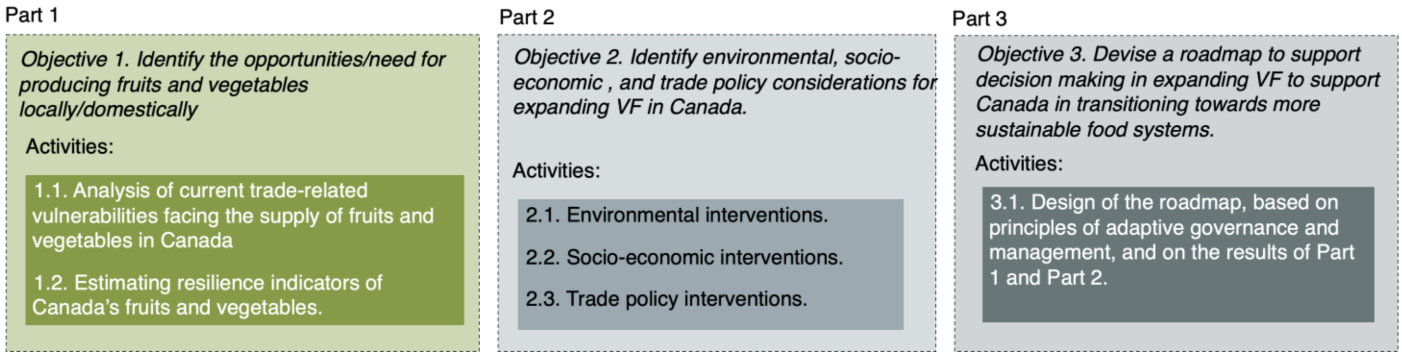

Figure 1. Methodology for devising a roadmap to guide decision-making in expanding VF in Canada.

2. Results

2.1. Current trade-related vulnerabilities facing the supply of fruits and vegetables.

The global interconnectedness of food systems, combined with geopolitical, health, climate, and sustainability challenges, has exposed vulnerabilities in supply chains. These trade-related vulnerabilities manifest through fluctuating and volatile food prices tied to supply dynamics. In 2022, the Canadian Consumer Price Index for food experienced its highest acceleration rate since the 1980s, reaching a staggering 11.4% monthly increase year over year (Blois, 2023). This increase far surpassed the country's average overall inflation rate, with the costs of nutritious foods such as fruits and vegetables rising by an average rate of 11.4% and 12.7%, respectively, between September 2021 and September 2022 (Charlebois, 2022).

A recent report from the Standing Committee on Agriculture and Agri-Food of Canada's House of Commons summarizes various factors contributing to high food price inflation in Canada (Blois, 2023). Global factors, such as "international supply chain disruptions and global price fluctuations in inputs such as feed, fuel, and fertilizers," and regional factors like "labor shortages and extreme weather events," were identified as drivers of food price inflation in the country (Blois, 2023). These factors underscore the supply chain vulnerabilities to global and regional events.

In a globalized food system where production and supply is concentrated in a few regions, a shock in one part of the well-functioning system can have cascading impacts throughout (Challinor et al., 2018). The Ukraine-Russia war, for example, resulted in unprecedented spikes in wheat and fertilizer prices beyond the region significantly impacting global food systems (FAO, 2022). With the increasing frequency of climatic and non-climatic shocks, these cascading impacts can lead to supply disruptions, significantly raising the prices of fruits and vegetables, thereby threatening Canadians' access to these nutritious foods (Ramankutty & Bajaj, 2024). This is particularly crucial as the high costs of these foods along with the lack of knowledge and preparation skills might be the leading drivers of insufficient consumption by Canadians (Charlebois et al., 2023). With increasing weather shocks and global warming, this issue is only set to worsen if not addressed (Bajaj, 2023).

The following section outlines specific trade-related vulnerabilities in Canada's supply of selected fruits and vegetables that can be grown domestically, either on-farm or under VF, offering an opportunity to diversify the supply and manage vulnerabilities.

Import Dependence and Lack of Diversity

Despite Canada being a net exporter of food, a significant portion of its fruit and vegetable needs relies on international imports. Notably, 80% of fruits and 60% of vegetables are sourced internationally (Bajaj, 2023; Kissinger, 2012). This heavy dependence on imports exposes Canada's fruit and vegetable supply to disruptions in international transportation, geopolitical tensions, conflicts, export embargos, and production losses due to extreme weather events in supplying regions. With a projected increase in the frequency and intensity of weather extremes, these vulnerabilities are expected to intensify in the future (Anisimov and Magnan, 2023).

Bajaj et al. (2024) suggest that the out-of-province dependence for fruits that can be theoretically grown in VF ranges from 0% to 100% (Bajaj and Ramankutty, 2024). With the exception of blueberries, cherries, and strawberries in a few provinces, over 75% of the supply of all fruits and vegetables comes from international or interprovincial sources. For example, the out-of-province dependence on cherries, except for British Columbia, ranges from 87% to 99% (data for Ontario and British Columbia shown in Figure 1). Similarly, most Canadian provinces rely on out-of-province supply for vegetables theoretically suited to grow in VF. Except for peas in Alberta, Ontario, and Quebec, carrots and turnips in eastern provinces and Manitoba, and lettuce in Quebec, all provinces depend on out-of-province supply for over 75% of their demand for vegetables that could potentially be grown within the province. The dependence on out-of-province supply is also substantial for leafy greens successfully grown in controlled environments. Except for Quebec, all other provinces source over 85% of their lettuce and over 90% of their spinach supply from out-of-province.

Trade-related vulnerabilities are more pronounced in supply chains lacking diversity in supplying regions. Any disruption in these concentrated supply chains poses a threat to the stable supply and affordable access to fruits and vegetables for Canadians. This was evident in recent lettuce and cauliflower shocks due to Canada's heavy dependence on California. Canadians experienced two to threefold price increases for these produce items due to droughts and pest shocks in California (CBC, 2023). Among the fruits and vegetables that can be theoretically grown in VF, the supply chain diversity of most provinces is lower than four countries[1]. Specifically, berries, papayas, cherries, carrots and turnips, peas, spinach, lettuce, and tomatoes are characterized by low supply diversity. At a national scale, Global Affairs Canada has also highlighted the lack of diversity in some of these supply chains (Jiang, 2020). As with out-of-province dependence, supply chain diversity also varies by province. For instance, Ontario has relatively higher diversity than British Columbia for blueberries and cranberries supply (Figure 2).

[1] Supply chain diversity is estimated using the food flows from Bajaj et al. (2024). Shannon diversity index, that accounts for both the number of supplying regions and the supply shares, is used as an indicator of supply chain diversity. The numbers represent the number of equally common sourcing regions. Supply diversity of two, for instance, represents a particular produce is soured from two equally common sourcing regions.

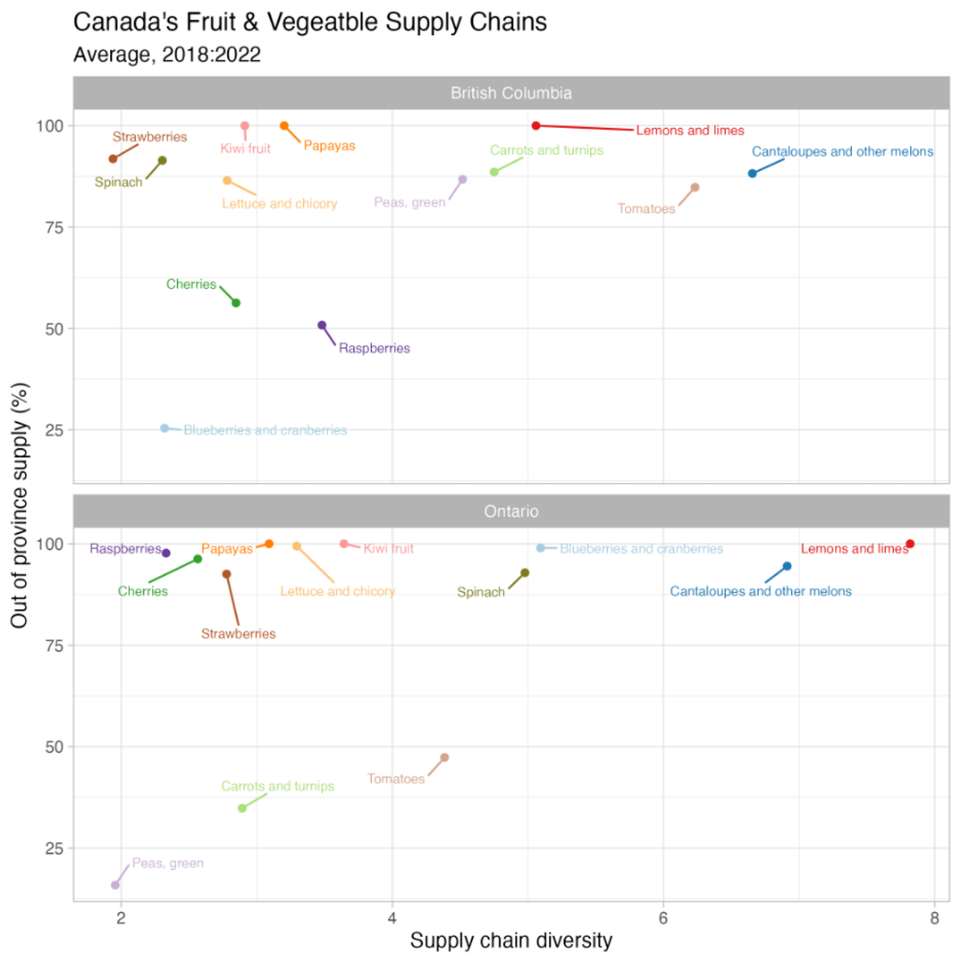

Figure 2. Average supply chain diversity (x-axis) and out of province dependence (y-axis) of selected fruits and vegetables for British Columbia and Ontario

Lack of Redundancies

Due to the high perishability and limited storage capacity, the supply chains of fruits and vegetables are particularly vulnerable to disruptions. With the exception of apples, potatoes, onions, and carrots, most fruits and vegetables degrade in quality within days or weeks (Burrows, 2021), providing only modest buffering capacities during disruptions. Furthermore, a significant portion of fruits and vegetables reaches Canadian provinces after traveling considerable distances. Approximately 92% of imported fruits cover distances exceeding 1500 km, with 22% extending beyond 7000 km (Kissinger, 2012). Much of this food is transported through road networks, where, excluding inter-provincial flows, Kissinger (2012) estimates that 77% of all vegetables and 44% of all fruits imported are transported by truck. The high reliance on a single mode of transportation, coupled with bottlenecks in Canada's road infrastructure, exposes the fruit and vegetable supply to transportation logistics vulnerabilities (CTA, n.d.; Jiang and Scarffe, 2021; Young, 2016). These vulnerabilities are even more pronounced in Northern remote communities. Additionally, the nutritional value of fruits and vegetables is compromised due to the large distances and time between harvest and consumption (York University, n.d.; Al-Dairi et al., 2021).

Beyond supply chain vulnerabilities, fruit and vegetable supply also has implications for Canada's transition towards environmentally sustainable food systems. The substantial travel distances and stringent climate-controlled transportation requirements contribute significantly to carbon emissions (Kissinger, 2012). Globally, it is estimated that transportation of fruit and vegetable contributes roughly twice the amount of emissions compared to their production (Li et al., 2022). Furthermore, Canada's consumption of fruits and vegetables contributes to the over-exploitation of already stressed groundwater aquifers in the United States (Marston et al., 2015).

Effective management of these vulnerabilities is crucial for Canadians to access nutritious diets. Several strategies can be employed, including diversifying supply chains, ensuring resilient transportation networks, building redundancies through alternate supply routes, sourcing regions, road and rail networks, and increasing domestic production both on-farm and under controlled environments (Bajaj, 2023). In the following sections, we delve into the environmental, socio-economic, and trade policy considerations of one such intervention—expanding domestic production of these nutritious foods through VF.

2.2. Considerations for expanding VF to support Canada in transitioning towards more sustainable food systems.

2.2.1. Overview of the VF sector in Canada

The types of crops currently produced in commercial VF units might be those allowing short production cycles, high harvest indexes, and high market values (Dsouza et al., 2023). Among fruit and vegetable crops, this includes leafy greens, vine crops, herbs, microgreens, and small fruits (De Oliveira et al., 2021). However, other crops studied in experimental VF units and/or conceptual models include energy-intensive crops such as wheat (Asseng et al., 2020) and potatoes (Kobayashi et al., 2022). Dsouza et al (2023) performed a systematic scoping review of studies on VF, suggesting that the most studied crops include lettuce, basil, and tomatoes, with lettuce accounting for over 50% of all studies. However, the authors documented that over 200 types of vegetables and 19 types of fruits have been studied.

The most common crop studied in VF is lettuce (Dsouza et al., 2020), but this crop represents 3% of the domestic vegetable supply in Canada (Government of Canada, 2023). Research on a wider range of crops is required to determine whether VF can be brought to scale, while ensuring sustainability of Canada's food system. Hence, identifying the demand for nutritious crops (in current and future scenarios) in each region/province and the context-specific enabling environment will be a critical step to guide future VF studies in Canada. This is aligned with the need for including VF in Canada's official reports on the supply of fruits and vegetables, which currently includes open field and greenhouse production, but there is no information on the size of the VF industry and on the characterization of their market in Canada.

2.2.2. Environmental considerations

An objective analysis of the environmental performance of food systems and of their components requires adopting a holistic perspective (Allen et al., 2019; Chaudhary et al., 2018; HLPE, 2014), which may be done by performing Life Cycle Assessment (LCA). The growing body of LCA studies applied to the agri-food sector in the last decade suggests widespread consensus on the need for adopting this approach to objectively compare the environmental impacts of producing crops and other goods with different farming methods. Existing LCA studies indicate that VF are typically more energy intensive than greenhouses and open-field farming systems, and that a significant share of their environmental impacts stem from their energy requirements (Martin & Orsini, 2023). However, a number of LCA studies suggest that VF may outperform greenhouses in terms of energy requirements in regions with extreme temperatures, as the latter lack the necessary infrastructure to ensure optimal efficiency of resources under these conditions (Graamans et al., 2018; McCartney & Lefsrud, 2018; Zhang & Kacira, 2020). Nonetheless, Casey et al. (2022) performed LCA to compare the environmental impacts of producing lettuce in VF vs. open field for different scenarios of electricity grids, concluding that the source of energy used has a greater impact on the environmental performance than the type of farming system (i.e., greenhouses, VF, or open field).

The strategies suggested in the literature for improving the environmental performance of VF often refer to implementing renewable sources of energies for electricity supply. However, accessing electricity grids based on clean sources of energy is often beyond the variables that may be controlled from the agri-food sector, and implementing off-grid renewables is not always feasible and may lead to trade-offs among other environmental categories (Li et al., 2020). Further approaches to enhance the environmental performance of CEA, including VF, include:

- Planning VF within a concept of a circular economy and/or implementing synergies with surrounding activities/businesses, to improve resource efficiency through shared flows of water, energy, and materials (Martin et al., 2022; Martin & Molin, 2019).
- Implementing dynamically controlled systems, which may improve resource efficiency and also enhance the nutritional value of crops (Cohen et al., 2022; Van Delden et al., 2021).
- Implementing hybrid systems (i.e., models combining features of different types of CEA) to leverage their features (e.g., greenhouses with vertical configuration of crops and/or artificial lighting), and of the natural environment (e.g., seasonal use of solar lighting).
- Maximizing the lifespan of CEA infrastructure and of other inputs used (Hawes et al., 2024; Martin & Molin, 2019).

Beyond CO2 emissions, the analysis of VF solutions must consider other environmental categories such as resource depletion, toxicity to ecosystems and hazards to human health (Hebinck et al., 2021). In fact, other inputs such as packaging, infrastructure, growing media, fertilizers, and transport processes might also play a significant role in their environmental performance (Martin & Molin, 2019; Martin et al., 2019; Martin et al., 2022; Martin & Elnour, 2023; Martin et al., 2023). The varied results among VF LCA studies suggest that this depends on multiple variables associated with their context (i.e., location, transport needs), design (e.g., number of levels, size and type of building, lighting, heating and cooling, automation level), plant science (e.g., temperature needs, growth media, yield, time of lighting, and use of fertilizers), and management (i.e., maturity of the system, expertise, technologies used).

In terms of operational energy requirements, the types of crops produced play a central role. Kobayashi et al. (2022) suggested quantities of direct energy uptake for producing crops in vertical farming ranging between 435 – 907 kWh/kg of wheat; 62 – 130 kWh/kg of potato; 16 – 34 kWh/kg of tomato; and 7 – 15 kWh/kg of lettuce. Although the water use efficiency varies per type of crop and design parameters, existing studies suggest relatively consistent orders of magnitude per farming method, ranging from 0.8 – 12 l/kg for VF; 1 – 24 l/kg for greenhouses; and around 250 l/kg for open field crops (Barbosa et al., 2015; Graamans et al., 2018; M. Li et al., 2022; Martin et al., 2022). Regarding ecotoxicity and toxicity to human health, some VF-LCA studies assume very little to zero agrochemicals for pest control (Casey et al., 2022; Martin et al., 2019, 2023; Martin & Molin, 2019; Nicholson et al., 2020; Ramin Shamshiri et al., 2018; Saraswat & Jain, 2021; Shao et al., 2022; Van Delden et al., 2021) while other studies refer to case studies where VF requires pest management (Avgoustaki & Xydis, 2020; Lubna et al., 2022; Van Delden et al., 2021).

The significance of the environmental impacts of VF for different impact categories depends on each context. For example, water savings might represent an opportunity in regions potentially exposed to droughts, such as the Canadian Prairie Provinces (Tam et al., 2019), whereas high energy requirements in the form of electricity might pose challenges in locations where continuity in energy supply is an issue, or where electricity supply with low-carbon technologies is not feasible. Further, the results of LCA studies are sensitive to the inputs of data used, and the use of reliable VF models to assess their environmental performance requires validation with real case studies (Liebman-Pelaez et al., 2021). Hence, reducing the uncertainty in future VF-LCA studies requires collaboration between VF growers and researchers, to help devising solutions that are environmentally sustainable, economically thriving, and socially adequate.

Studying the environmental performance of VF: steps forward.

The traceability of the results of VF-LCA studies remains challenging not only because of the multiple variables involved in the farming method studied, but also considering the scope of each LCA study, including the selection of the functional unit (FU), and system boundaries. While most existing LCA studies applied to producing fresh fruits and vegetables define the FU in terms of mass unit (e.g., a kg or t of specific fruits/ vegetables), the adequateness of this approach has been subject to debate, especially for performing comparative assertions. Examples of this include lightweight crops such as herbs, or organic produce often characterized by lower weight per unit, which might end up being penalized with mass based FUs (Dorr et al., 2021). Some authors suggest defining the FU in terms of the ultimate function of fruits and vegetables and therefore, using servings (e.g., USDA servings) to align with dietary needs (Hawes et al., 2024) or in terms of their nutritional value (Parajuli et al., 2019). The latter approach requires acknowledging that the function of fresh fruits/vegetables is not limited to their nutrient content, but they also play a role in people's dietary choices, in supporting healthier diets, and culturally. The task of performing objective comparisons becomes even more challenging when considering that the nutritional value of crops is sensitive to multiple factors that include the environmental conditions (e.g., temperature, lighting, quality of growth media), ripeness at time of harvest, yield intensity, and conservation measures (e.g., packaging, temperature in transport processes), among others. Provided the sensitive nature of fruits and vegetables to preserve their quality and nutritional value, the period of time between production and consumption might affect substantially their nutrient content (Eaves & Eaves, 2018; Parajuli et al., 2019), which might represent an advantage for scenarios of local production.

The readily changing contexts resulting from the dynamics of the environmental, socio-economic, and technological dimensions demand estimating metrics of environmental performance for potential future scenarios, which may be assessed using prospective LCA (Parajuli et al., 2019). This means that studies on the sustainability of food systems and of their components facing the future must deal with uncertainties in terms of technological innovations, future demands of fruits and vegetables, pest management needs, and potential changes in productivity for different climatic zones, among others (Parajuli et al., 2019). Existing studies suggest that the rising global temperatures might be detrimental for producing crops in tropical regions, while it might favor crop production in the northern regions, including Canada (Parajuli et al., 2019). This, along with the increasing demand for fresh food in cities stemming from continuous migration and urbanization processes (Langemeyer et al., 2021) might not only have an impact on the dynamics and pathways of international trade of fruits and vegetables, but also on the environmental impacts associated with benchmark scenarios of open-field production and imports. Further, the sensitive nature of fresh fruits and vegetables entails considerable amounts of spoilage during the post-harvest stage without optimal management of temperature across their supply chain. This might lead to increased refrigeration needs along the storage and transportation stages to preserve freshness and nutritious value, potentially leading to increased electricity demands for scenarios of open-field production and imports (Parajuli et al., 2019).

2.2.3. Socio-economic considerations

Consumer Acceptance and Perception of VFs

Most existing studies on VF are focused on assessing the technological, environmental, and economic viability of these facilities, while their social sustainability remains relatively unexplored (Dsouza, Newman, Graham, & Fraser, 2023). Therefore, limited attention has been given to investigating aspects such as social and cultural implications of VF, as well as labour dynamics, and community awareness and involvement. The potential contribution of VF to the sustainability of food systems has been questioned not only because of their energy intensity, but also due to high start-up costs and consumer accessibility (Broad, Marschall, & Ezzeddine, 2021). Further, there is still uncertainty among consumers facing VF due to their perceived lack of naturalness, and their benefits and risks in terms of their social, environmental, and economic impacts which vary depending on how vertical farms are built and implemented (Mina et al., 2023).

Addressing social aspects is crucial for a comprehensive understanding of the implications of expanding VF. The analysis of social and policy interventions is a necessary step to help identifying areas where Canadian governments can invest to increase awareness and reduce resistance to the consumption of food produced in artificial environments such as VF. Identifying the barriers that stakeholders (i.e., consumers, producers, investors, and researchers) are facing to further develop VF will provide insights into potential areas of investment. This understanding can contribute to enhancing affordability, improving public perception, fostering social acceptance, facilitating smoother regulatory processes, and increasing the widespread use of VF.

Technological progress in general terms is often viewed positively, but novel technologies related to food production have faced higher resistance from consumers (Siegrist and Hartmann, 2020). Siegrist and Hartman argue that when consumers lack knowledge and are not familiar with new food technologies, they rely on simple heuristics like "natural is better" or depend on their emotional responses to evaluate food technologies, form perceptions, and make purchase decisions instead of logical evaluation. Therefore, the perception of how VF may contribute to sustainability among consumers is important, in addition to the affordability concerns. Even when Food Safety officials have assured that food produced using novel food technologies is safe and must pass multiple regulatory and safety tests and processes, the perception of VF produce as unnatural continue to impede widespread use and trade of such products. According to Broad et al. (2021), there is evidence of potential for increasing public awareness and understanding of VF and more needs to be done in changing the perception that food grown in a controlled environment agriculture is "unnatural".

Strategies to Enhance Public Awareness and Acceptance of VF

Numerous studies have identified that education and exposure as well as providing accurate and adequate information can lower consumer resistance to new food technologies (Siddiqui et al., 2022; Yano, Maruyama, Lu, & Takagaki, 2023; H. Zhou, K. Specht, & C. K. Kirby, 2022). In addition, creating opportunities where people can witness and interact firsthand with the technology as well as disseminating information about its scientific mechanisms have been found to improve positive perception about crop cultivation using artificial lighting (Yano et al., 2023). A study in China that examined the acceptance of VF found higher levels of acceptance in urban contexts when high energy uses are explained, for example, as energy that would have been wasted, such as waste heat and organic waste (Zhou et al., 2022). A study in the US found that attitudes towards VF was favorable, particularly in terms of their potential for addressing environmental concerns and lowering food production costs (Coyle and Ellison, 2017). However, there was less certainty regarding the naturalness of food grown in VF and whether it is healthier than traditional grown produce. Mina et al. (2023) performed a systematic review of existing studies addressing consumer perceptions and social sustainability of VF, suggesting the need for implementing multifunctional VF facilities as a means of engaging stakeholders and local communities, to thrive in providing socio-economic benefits.

A major social concern with regards to VF is skepticism around their potential contribution to true sustainability (Jürkenbeck, Heumann, & Spiller, 2019). Since these technologies often require relatively higher levels of investment, infrastructure, and energy inputs, the produce from VF can be more expensive as compared to that produced with other farming methods. This can create issues around the accessibility of fresh, locally grown produce for low-income communities and tarnish the idea of VF as solving accessibility and affordability problems of fresh produce. Another major issue with VF is the public perception that they are not accurately portrayed as a sustainable way of farming due to the significant amount of energy needed to control the growing environment, which the public might perceive to be associated with increased greenhouse gas emissions. VF might also be perceived as facilities requiring large amounts of water and, therefore, as diverting this resource from other essential uses, especially around urban centres. In contrast, a study on Arizona lettuce growers suggests that two out of three CEA leafy green producers use roughly 90% less water than their traditional counter parts (Global CEA Census Report, 2021). This suggests the need for enhancing the availability of evidence-based studies on the sustainability of VF to the public.

According to the 2021 Global Controlled Environment Agriculture Census Report, which is a census mainly focused on growers but also providing information on the perspective of suppliers and researchers, some of the main concerns facing VF include their intensive energy consumption, significant initial investment costs, and reliance on non-renewable materials such as plastics, which contributes to VF being perceived by the public as unsustainable (Global CEA Census Report, 2021). However, these issues can be minimized through community engagement and participation, and with education around resource-efficient technologies and, potentially, sources of renewable energy utilized by VF. Further providing information on the performance of VF through transparency will help raise awareness among farmers, consumers, and policy makers about the potential benefits of CEAs in terms of reduced water use, year-round-production, lower pesticide use, fresher, and lower transportation costs, which may result in increased support for CEA, including VF. The Global CEA census report indicated growers believe food security and water usage areas the top sustainability issues they are addressing in their business but are aware of the trade-offs that exist in term of the sustainability of their operations and outcomes. They have also indicated energy and plastic use to be areas with room for improvement. Therefore, it is important to undertake research to develop the evidence, increase awareness through communication, engagement and facilitate direct interactions while at the same time being transparent and acknowledging some of the trade-offs that exists within the VF to build trust and increase public acceptance. As Broad et. Al., (2021) point out, to be successful, CEA needs to meet the public's approval as an environmentally, economically, and socially sustainable alternative that complements traditional food production. They further point out that social concerns should be taken into consideration if VF is to be integrated in broader food system.

VF might also be seen as disrupting traditional agriculture and causing challenges for farmers to adopt them or keep up with the high-tech methods or potential better prices offered by them. As most vertical farms are expected to be or are already located near urban populations, it might reduce the economic benefits available to traditional agriculture areas and the increased automation and technology might create a loss of jobs in traditional agriculture. However, there is limited empirical research to validate the food security and community development advantages of VF (Dsouza et al., 2023). Robust research in this area is needed to fully understand the impact widespread uptake of VF has on community development and food security.

2.2.4. Trade Policy considerations

Challenges

Notwithstanding their prospects for supply-chain resilience, domestic food security, and climate change adaptation, VF faces challenges related to high start-up and operational costs ranging from energy and labour to other overhead costs, escalated by the current inflationary pressures (Dohlman et al., 2024). Owing to the long-term development cycles of aggritech start-ups and investors' emphasis on positive cash flow generation in the current macroeconomic environment, VF has faced various challenges ranging from layoffs to bankruptcies (Brennan et al., 2024). The downward pressure exerted by imports from low-cost producers also exacerbates cash flow problems for domestic VF growers and impacts their competitiveness (United States International Trade Commission [USITC] 2021). Further, the disparity between levels of environmental cost internalization between domestic and imported fruits and vegetables also raises concerns about competitiveness. While these challenges appear to diminish the competitiveness and viability of VF as domestic alternatives to Canada's fruits and vegetable supply and backstops for supply chain disruptions, they continue to attract interest from investors focused on long-term growth (Brennan et al., 2024). However, the outlook is considerably different for Canada's northern communities. Their remote and isolated geographical locations, the lack of transport infrastructure, and harsh winters make access to and affordability of fruits and vegetables particularly difficult. For these communities, which experience high costs of shipping and storage of fruits and vegetables, dependence on inter-provincial and international trade results in a disproportionately higher rate of food insecurity than the rest of Canada (Leblanc-Laurendeau, 2020). These communities are also at risk of considerably worse food insecurity in the event of supply-chain disruptions.

VF have been explored as potential solutions to food insecurity in northern communities (Leroux & Lefsrud, 2021; Verhoeven, 2021). However, the peculiar challenges of these communities speak to a lack of conditions that contribute to an enabling environment for sustainable VF enterprises. Northern communities generally struggle to attract agri-food investments due to a shortage of suitable land for agriculture, lack of infrastructure, high cost of utilities, and lack of skilled labour. Energy is particularly costly and unsustainable in off-grid northern communities owing to a higher-than-average reliance on diesel-fired electricity generation (Canada Energy Regulator, 2018). This means even higher operational costs and carbon footprint for businesses in remote northern communities, making it unfeasible for VF to substantially abate the high costs of fruits and vegetables in these communities.

Government Support: A Brief Overview of the Policy Space and WTO Disciplines

The challenges confronting VF invite some consideration of government programs designed to support the resilience and sustainability of Canada's domestic fruits and vegetable supply chain. The extent and structure of Canada's support programs for VF may be influenced by WTO commitments, the policy objective of support initiatives, and the impact of such support programs on the market. Government support or subsidies tend to pursue the dual objective of improving economic performance and achieving social objectives in specific industries or regions where markets fail to allocate resources efficiently (Lester, 2018). Two key objectives in the context of government support for VF are the economic objective of improving their competitiveness to ensure resilient domestic fruits and vegetable supply chains and the social objective of ensuring food security in remote northern communities. The WTO Agreement on Agriculture defines ceilings on certain direct and indirect subsidies that can be provided for agricultural producers and allows some policy space for domestic agricultural support. The principal objective of the Agreement is to minimize subsidies that can lead to distortions in agricultural trade. Accordingly, government support measures, which may be in the form of public spending on grants and loans (budgetary payments) or tax exemptions (revenue forgone), are required to satisfy the criteria for exemptions contained in Art. 6.2, Art. 6.5 and Annex 2 of the WTO Agreement on Agriculture and the spending limits for non-exempt measures known as Aggregate Measure of Support (AMS). Exemptions under Article 6.5 and Annex 2 of the WTO Agreement on Agriculture are commonly understood as blue box and green box exemptions, respectively. The exemptions under Art. 6.2 are provided specifically for developing countries. The 'amber box' is the term commonly used for non-exempt or restricted support measures required to be within the spending limits of states' levels of commitments (Brink & Orden, 2023, p. 23).

The green box has a notably broad scope that can accommodate a wide range of government support programs exempted from spending limits and can be leveraged to support VF. Support measures within the green box are subject to the fundamental requirement that they have no, or at most, minimal distortions on production and trade. Further, they must meet the basic criteria of being provided through publicly funded government programs, which involve neither higher consumer charges nor price support to producers. In addition to these general criteria, various categories of measures are subject to policy-specific criteria. For instance, government support for the provision of public services to agriculture, such as research, training, extension, and advisory services to facilitate the transfer of research results to farmers, marketing and promotion support, and generally available infrastructure services, including energy, are required to exclude direct payments to producers. The green box also exempts from spending limits direct payments to producers through grants, revenue forgone (i.e., tax incentives), and payments in kind for various objectives governed by specific criteria. Such direct payments include compensation for the extra cost of compliance with environmental policy requirements, which may cover expenses for adopting sustainable production methods to conform with regulatory requirements. (WTO Agreement on Agriculture, 1994, Annex 2, Paragraph 12). Paragraphs 6-11 of the Agreement provide for other direct payments, such as decoupled income support, government income insurance and income safety-net programs, reliefs from natural disasters, and various structural adjustment assistance (through producer and resource retirement programs and investment aid) and regional assistance programs subject to various specific criteria and a common requirement that such payments are related to product prices.

The key distinction between the green and blue box exemptions is the express requirement of zero or minimal trade-distorting effects for green box-exempted support (Brink & Orden, 2023). While blue box-exempted support programs under Art 6.5 of the WTO Agreement on Agriculture may be considered to have some degree of trade-distorting effects, they also require producers to limit production, thereby decreasing their trade-distortive effects. Thus, blue box program exemptions are considered to fall somewhere between the green and amber box subsidies (Holden, 2005). Agricultural support programs with trade-distortive effects are categorized under the amber box and subject to limits on the Aggregate Measure of Support based on commitments by WTO member States. Canada's commitment with respect to the maximum Aggregate Measure of Support is CAD4.301BN. On the other hand, the Current Total Aggregate Measure of Support (CTAMS) for the year 2020 was CAD1.199 BN, which is CAD 3.1BN below Canada's commitment level (WTO Committee on Agriculture, 2023). The value of direct payments to agriculture producers in 2022 (CAD7.345BN) suggests that much of Canada's agricultural support programs explore the policy space within the green box (Statistics Canada, 2023). Canada's notifications to the WTO on domestic support also indicate that there is ample room within the amber box limits to support VF in consistency with WTO disciplines.

Support for R&D

Subsidies that aim to enhance economic performance generally prompt trade policy concerns. In this light, subsidies designed to enhance the competitiveness of VF through financial contributions or benefits may be considered trade-distorting and countervailable by Canada's trading partners. Support measures determined to have significant trade distortions occasioning adverse effects on other WTO members would be inconsistent with the provisions of the WTO Agreement on Agriculture and the Agreement on Subsidies and Countervailing Measures (*United States – Subsidies on Upland Cotton*). The existence or absence of trade distortive effect of agricultural support is a question of fact that could be disputed by WTO member states. Indeed, Canada challenged support programs of the United States in 2007 on the grounds of trade distortion *(United States – Subsidies and Other Domestic Support for Corn and Other Agricultural Products* [DS357] pending). Subsidies with economic objectives have also been associated with economic harm and lagging productivity. The prevailing fiscal environment, in which government spending is under increased public scrutiny for its role in the current inflation (Shecter, 2023), places the design and implementation of government support under the spotlight. These trade and overall economic concerns narrow an otherwise broad policy space for providing government support to VF. Therefore, the challenge is ensuring that policy design, implementation, and oversight of agricultural support for VF is structured to enhance economic productivity while minimizing market distortions and inefficiencies. Brink and Orden (2023) note that "productivity growth over time can improve both the food availability and access dimensions of food security." One area that can be explored to support the efficiency of VF provisions is the green box policy space for research and development (R&D) assistance as a public service, excluding direct payments to producers. R&D support can complement academic and private sector-led R&D initiatives, such as the RBC Foundation's support for research and infrastructure for talent development in controlled environment agriculture (Olds College of Agriculture and Technology, 2023). The federal and provincial governments provide R&D support through various research and development centres across the country. These can be leveraged with R&D partnerships with academia, investors, and industry to develop global leadership in VF innovation and adoption. Increasing innovation synergies between government, researchers and industry can contribute significantly to lowering VF costs, making them more competitive, and facilitating the translation of research results into scalable, profitable, and efficient agribusinesses.

Environmental Performance-Based Support

Competitiveness concerns arising from domestic regulatory requirements for the mitigation and internalization of environmental costs have been the subject of trade policy discussions concerning Border Carbon Adjustments (BCAs) or Carbon Border Adjustment Mechanisms (CBAMs). These mechanisms are yet to be extended to agri-food products under existing initiatives. BCAs seek regulatory equivalence between domestic and imported products by applying domestic carbon prices to imports based on their carbon footprints. Current regulatory initiatives are dependent on the availability and comparison of carbon footprint data between domestic and imported products based on actual or default values. While Canada is yet to adopt a BCA mechanism, addressing competitiveness concerns in the fruits and vegetables sector through BCAs could trigger trade policy and food security concerns. However, the WTO Agreement on Agriculture permits government support in the form of compensation for the cost of compliance with environmental regulatory requirements (WTO Agreement on Agriculture, 1994, Annex 2, Paragraph 12). This policy space can be explored to provide rebates or other forms of support to VF growers based on environmental performance, even without a BCA mechanism.

Support for Northern Communities

VF can provide much-needed local production of fruits and vegetables in isolated northern communities. However, subsidies would be crucial to assisting VF growers in navigating the challenges of operating viably and sustainably in these communities. Government support with the social objective of enhancing the expansion, viability, and adaptation of VF to the needs of northern communities and harnessing their potential for a reliable, sustainable, and affordable fruit and vegetable supply to address food insecurity may be more easily justifiable. For instance, the provision for direct payments to producers in defined disadvantaged regions (regional assistance programs) under the green box may also be explored for Canada's remote northern communities based on spelt-out criteria indicating the difficulties concerning fruits and vegetable supply arising from inherent circumstances of the region (WTO Agreement on Agriculture, 1994, Annex 2, Paragraphs 6-11, 13).

Existing subsidy programs for remote northern communities can be retooled or expanded to support the expansion of VF in these communities. Support for developing and retaining local skilled labour in these communities would also be crucial. Current initiatives, such as Nutrition North, provide retail subsidies to businesses, including greenhouses, other growing facilities, and retailers in eligible communities. However, these initiatives do not address the root causes of high food prices in northern communities and have been ineffective in addressing the disproportionately high cost of food in northern Canada (Li & Galloway, 2023). The nature of support contemplated needs to extend beyond conventional subsidies intended to be passed through to consumers. Critical infrastructure gaps in northern communities need to be bridged, including the development of affordable and sustainable energy projects to reduce energy costs and ensure the sustainability of VF. As noted earlier, government support through the provision of infrastructure is permitted under the green box. Accordingly, the capacity of clean energy projects in northern territories supported under initiatives such as the Northern Responsible Energy Approach for Community Heat and Electricity (REACHE), the Clean Energy for Rural and Remote Communities (CERRC), and other regional energy strategy programs can be expanded to accommodate access to clean energy for VF, thereby attaining both energy and food security goals.

Further, the high cost of capacity building and the shipment of both equipment and labour to facilitate the operation of VF in northern communities can be considered eligible costs for subsidies. The Local Food Infrastructure Fund (LFIF) program, which ended on March 31, 2024, was designed to support projects relevant to food systems such as greenhouses, irrigation systems, garden equipment, and energy systems. Such programs could be assessed to consider their performance and the possibility of extension, improvement, or replacement to ensure that they translate to concrete results in terms of ensuring the viability of VF as integral parts of the local food systems in remote northern communities. One aspect to consider in such an assessment is the possibility of a significant upward review of the maximum funding amounts for such infrastructure projects.

3. Roadmap to support decision making on VF in Canada

The preceding sections provided insights into the complexity of the variables defining the potential contribution of VF to more sustainable food systems. The expansion of VF in the Canadian food system requires comprehensive understanding of the complexity, uncertainty, and rapidly changing innovations in the agriculture space. Future efforts by various stakeholders, like researchers, entrepreneurs, policymakers, and public and private funding agents need to consider the context in which VF is planned, as well as understanding the desired goals of their implementation, while devising strategies that mitigate potential trade-offs across multiple sustainability goals (Romero, 2023). Further, implementing VF as potential solutions in the long term must follow decision-making pathways structured to allow flexibility to ensure adequateness in spite of continuously changing contexts (Westley et al., 2011), while reducing the uncertainties associated with processes of innovation and transformative change (Walker, 2004). This means envisioning potential future scenarios of population dynamics, dietary choices, and climatic conditions, and requires decision-making supported by multistakeholder dialogues, where people play a central role both as active actors with the ability to introduce changes and to help reducing uncertainty through their knowledge (Seyfang, 2007), and as subjects of sustainability needing access to improved standards of living (Clark & Harley, 2020).

In light of multiple sustainability considerations discussed in the previous sections, we adopt the principles of *adaptive governance* and *adaptive management* (Dietz et al., 2003; Gunderson & Holling, 2002) to devise our roadmap (Figure 3). We use this approach to help align global sustainability goals with context-based institutional arrangements, while also providing flexibility to manage uncertainty in change making processes (Gunderson & Holling, 2002; Dietz et al., 2003. The value of this approach lies in the possibility of attaining meaningful outcomes through articulated action, while empowering communities to find solutions that meet their needs, reducing uncertainty risks in innovation processes, and conciliating multiple sustainability perspectives (Dietz et al., 2003). Further, in an active-adaptive management system, decisions are made based on ongoing monitoring and evaluation of the dynamics in the program. This involves actively adjusting management strategies and actions in response to changing conditions and new information, aiming to improve outcomes and achieve desired objectives. A key feature of developing adaptive capacity in management is continuous measurement and assessment of results to develop predictive capacity and assess the responsiveness of actions and relevance of results (Gibson, 2006). This leads to an iterative process that allows for flexibility and learning, enabling utilization of previously acquired knowledge during policy change or adjustments (Bahati & Bauer, 2010).

Early literature suggests that decision making in adaptive management must be based on steps that allow reducing uncertainty while implementing mechanisms to reorient decision making along development processes (Holling et al., 1978), which shares similarities with the precautionary principle in environmental management. Further, research intended to reduce this uncertainty requires asking the right questions, which might be best guided through policy concerns (Holling et al.,1978 pp 4). Hence, defining and prioritizing the desired outcomes of a sustainable food system, although challenging and dependent of each context (Hebinck et al., 2021), is the navigation chart and starting point for decision-making involved in potential policies, incentives, investments, and further research on VF in Canada. From the takeaways of Section 2, some desired outcomes that might be highlighted for Canada's food system include attained competitive environmental performance for crop production (relative to current/future benchmark scenarios of imports + open field/greenhouse production), stabilized prices in the supply of fresh fruits and vegetables, and enhanced access to affordable, healthy, and nutritious diets.

Once the guiding policy concerns are defined, further steps to progressively combine top-down and bottom-up approaches in adaptive management might be envisioned as suggested by Edwards (2010), cited by Westley et al. (2011, pp 771):

- "engage" (**listen and learn** about local ideas), **listen and learn** about local ideas),
- ''**educate**'' (inform local populations of resources and possibilities available),
- **"empower"** (trust in the potential and resourcefulness of local communities, including their long-term memory of traditional responses)
- **"encourage"** (allow a diversity of innovative responses to emerge, as opposed to insisting on a top-down planning process)"

The roadmap below incorporates the aforementioned elements of adaptive governance and adaptive management and, therefore, involves the participation of diverse stakeholders at different scales, reducing uncertainty, and providing flexibility to design appropriate and adaptive solutions for continuously changing contexts. The roadmap is structured in seven (7) key iterative steps, namely: i) Define (rationale); ii) Listen (stakeholder engagement); iii) Learn (state of art); iv) Assess (sustainability analysis); v) Manage (trade-off analysis); vi) Enable (policy interventions); and vii) Design (adaptive management program).

4. Conclusions

About 80% of fruits and 60% of vegetables consumed in Canada are sourced internationally. This heavy dependence on imports for fruits and vegetable supply exposes the supply chain in Canada to disruptions. VF can enhance the nationwide and provincial potential for the year-round local/regional production of fruits and vegetables in enclosed CEA facilities, although their potential role in Canada's food system remains largely unexplored. Further research must be guided by the desired outcomes of their implementation in Canada and focused on the types of crops needed in current and future scenarios of fruit and vegetable demand.

Notwithstanding their potential for mitigation of trade-related vulnerabilities and environmental impacts of global supply chains, VF poses various challenges bordering on high start-up costs, competitiveness concerns and energy intensity. Further, the relatively high costs associated with VF and the knowledge gap between VF producers and consumers may give rise to perception issues regarding the cost, sustainability and quality of fruits and vegetables grown in VF.

VF may be designed and situated in locations with access to clean energy, which requires considering current and future scenarios of energy grids, as well as evaluating the feasibility of implementing off-grid renewable energy systems. Further, there is room to improve their design, operation, technologies used, and management to optimize their environmental performance. Reducing uncertainty in future VF-LCA studies requires collaboration between VF growers and researchers, to help devise solutions that are environmentally sustainable, economically thriving, and socially adequate.

Public engagement on the environmental, economic, and food safety benefits of VF would be crucial to their acceptance by consumers and other stakeholders in the Canadian fruit and vegetable supply chain. Support for VF through public investment in research, access to capital, energy and water infrastructure, and resource management technology can be structured in accordance with WTO law to enhance the sustainability, economic productivity, and resilience of Canada's domestic fruits and vegetables supply chain. Existing support programs for northern communities can also be expanded to enhance the viability and sustainability of VF by ensuring access to clean and affordable energy. Providing flexibility in program and policies design through active-adaptive management system is needed to utilize the insights obtained from feedback and learning through onsite application and expansion of VF projects.

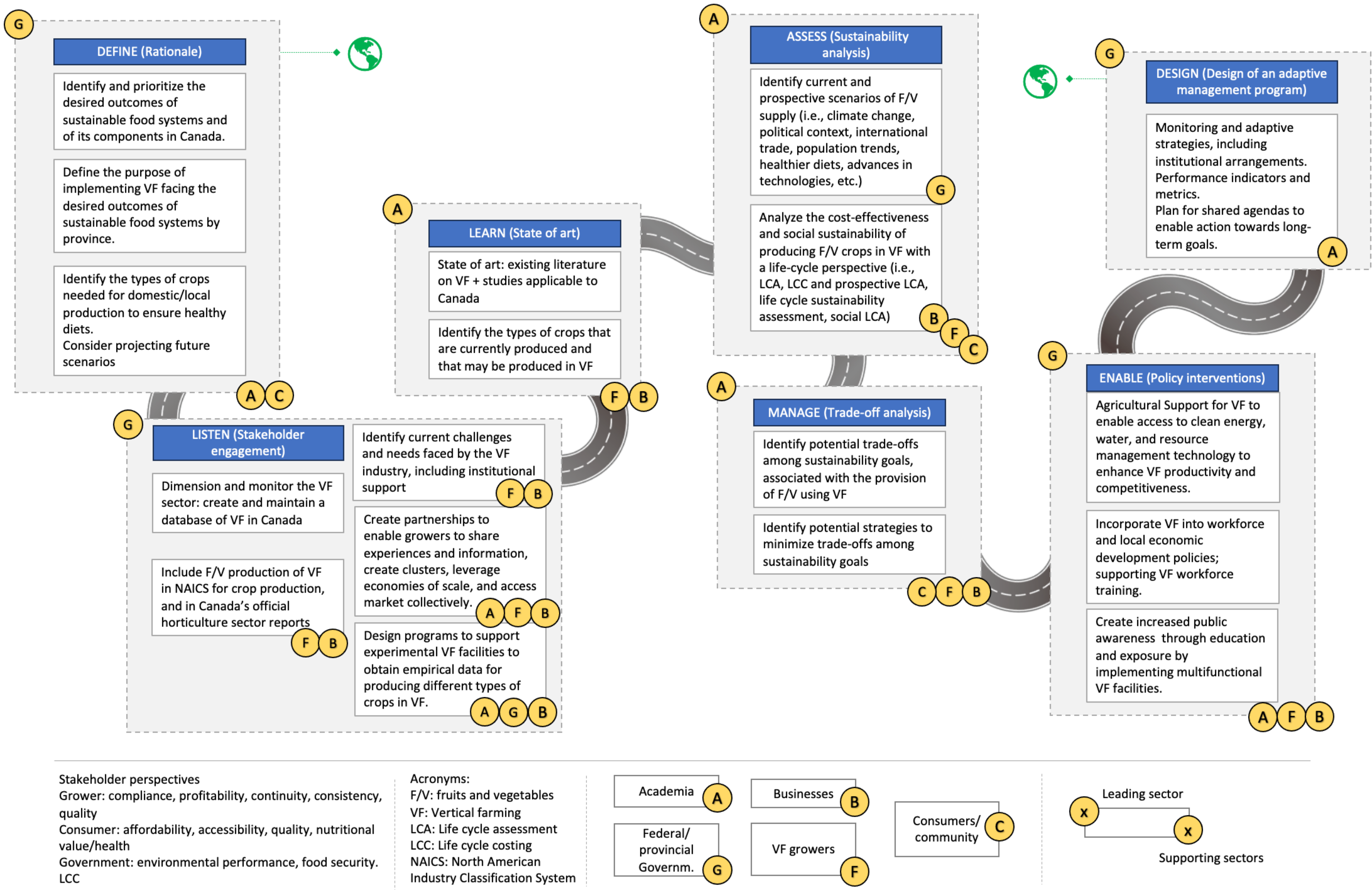

Figure 3. Proposed roadmap to support decision making for implementing VF in Canada.

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